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DATA PAPER

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Regionally aggregated, stitched and de-drifted CMIP-climate data, processed with netCDF-SCM v2.0.0

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Abstract

The world's most complex climate models are currently running a range of experiments as part of the Sixth Coupled Model Intercomparison Project (CMIP6). Added to the output from the Fifth Coupled Model Intercomparison Project (CMIP5), the total data volume will be in the order of 20PB. Here, we present a dataset of annual, monthly, global, hemispheric and land/ocean means derived from a selection of experiments of key interest to climate data analysts and reduced complexity climate modellers. The derived dataset is a key part of validating, calibrating and developing reduced complexity climate models against the behaviour of more physically complete models. In addition to its use for reduced complexity climate modellers, we aim to make our data accessible to other research communities. We facilitate this in a number of ways. Firstly, given the focus on annual, monthly, global, hemispheric and land/ocean mean quantities, our dataset is orders of magnitude smaller than the source data and hence does not require specialized 'big data' expertise. Secondly, again because of its smaller size, we are able to offer our dataset in a text-based format, greatly reducing the computational expertise required to work with CMIP output. Thirdly, we enable data provenance and integrity control by tracking all source metadata and providing tools which check whether a dataset has been retracted, that is identified as erroneous. The resulting dataset is updated as new CMIP6 results become available and we provide a stable access point to allow automated downloads. Along with our accompanying website (cmip6.science.unimelb.edu.au), we

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believe this dataset provides a unique community resource, as well as allowing non-specialists to access CMIP data in a new, user-friendly way.

KEYWORDS

aggregate, climate, CMIP, model, projections

1 | INTRODUCTION

Coupled atmosphere-ocean earth system models are our most comprehensive representations of the climate system. Earth system models from around the globe are currently running as part of the Sixth Coupled Model Intercomparison Project (CMIP6, Eyring et al. (2016a). CMIP6 builds on the Fifth Coupled Model Intercomparison Project (CMIP5, Taylor et al. (2012)), the output of which is still widely used. Combined, these two projects represent our most comprehensive, physically based estimates of the coupled earth system's behaviour under a wide range of experiments.

However, CMIP5 and CMIP6 models are computationally expensive hence cannot be run for all applications of interest. To fill this gap, a number of so-called reduced complexity climate models (also referred to as 'simple climate models') have been developed (Nicholls et al., 2020). An important part of developing such models is calibration: deriving a set of parameters, which allows them to best replicate the behaviour of the more complex models, which participate in the CMIP experiments. In order to do this calibration, one must first process the output from CMIP5 and CMIP6.

Once complete, the CMIP6 archive will be one of the world's largest data archives, with an expected total volume in the region of 18PB (Balaji et al., 2018). Fortunately, reduced complexity climate modellers typically only require annual-mean or monthly model output on hemispheric and land/ocean scales. This significantly reduces the volume of data they must handle. Nonetheless, reduced complexity climate models typically include a number of different modules, which cover the full range of the emissions-climate change cause-effect chain. Calibrating all of these different modules requires handling several datasets, such that the total volume of raw CMIP output of interest to a 'comprehensive' reduced complexity climate model will still be of the order of 50TB. Processing a data volume of this size is an intimidating task, even for expert users.

The data processing is further complicated by five extra factors. The first is that the raw data are all in the custom, climate-specific netCDF data format (Unidata, 2020). Without specialist training, it cannot be read, let alone analysed. The second factor is that the data are all sorted according to a highly regularized data reference syntax (Balaji et al., 2018). Such regularization is required to make the data able to be processed by machines; however, it can be confusing for non-experts. The third factor is that data are typically presented in absolute values. However, reduced complexity climate models are typically perturbation models; that is, they calculate perturbations from some reference state rather than absolute values. Given the data volume and sometimes complex relationship between CMIP experiments, calculating such perturbations for a large data volume is not a trivial task. The fourth factor is licensing. All CMIP5 and CMIP6 files are released under a specific licence which users must adhere to, and retrieving this information is not easily done. The final factor is retractions, that is removal of data, which is later identified as erroneous. Such retractions are essential to avoid erroneous results propagating into the scientific literature. However, at the moment there are only a limited amount of tools which allow a user to check whether they are using a retracted dataset or not.

The target audience for this dataset is reduced complexity climate models and modellers. Here, reduced complexity models refer to models which focus on global- and annual-mean properties of the climate system. As a result of their limited spatial and temporal resolution, reduced complexity models are very computationally efficient. These models are typically used when more complex models, such as those participating in CMIP, are too computationally expensive to use. For example, reduced complexity models are used within many integrated assessment models to assess the climate implications of different emissions pathways (given that integrated assessment models typically require hundreds to thousands of climate realizations, using CMIP models is not computationally feasible). Some prominent examples of reduced complexity models are MAGICC (Meinshausen et al., 2011), FaIR (Smith et al., 2018) and hector (Hartin et al., 2015). A detailed discussion of reduced complexity models and an overview of models available in the literature can be found in the first phase of the Reduced Complexity Model Intercomparison Project (Nicholls et al., 2020).

Our CMIP5- and CMIP6-derived dataset was extracted using the open source tool we developed, netCDF-SCM (netCDF handling for reduced complexity/simple climate modellers, see Section 2.2) and is ready for use by reduced complexity climate modellers. It is the result of addressing all the complications described above and includes global, hemispheric, land/ocean annual and monthly means of a variety of CMIP5 and CMIP6 output. Given the processing performed, this dataset is orders of magnitude smaller than the original data. The reduced data volume means that we can feasibly provide the data in a text-based format. Thus, while the dataset is targeted at developers of reduced complexity climate models, its simple, text-based format also allows non-expert users beyond the climate science community to read and analyse the data as they no longer need to engage with the climate-specific netCDF format.

2 | DATA DESCRIPTION AND DEVELOPMENT

2.1 | Datasets

To produce this derived dataset, we rely on the CMIP5 and CMIP6 archives (available via esgf-node.llnl.gov/search/cmip5/ and esgf-node.llnl.gov/search/cmip6/, respectively, last accessed 25 June 2020), both of which rely on the Earth System Grid Federation (Williams et al., 2011; Cinquini et al., 2014; Williams et al., 2016). Accordingly, any use of our derived set must also follow the conditions of the original data source and users should cite the relevant work of each modelling group whose output they use. Full details for CMIP5 can be found at pcmdi.llnl.gov/mips/cmip5/terms-of-use.html (last accessed 25 June 2020), and for CMIP6 at pcmdi.llnl.gov/CMIP6/TermsOfUse/TermsOfUse6-1.html (last accessed 25 June 2020).

To date, we have processed data from over 400 different CMIP6 model-experiment pairs and over 125 CMIP5 model-experiment pairs (Tables 1 and 2). We have built a custom software package, netCDF-SCM (further details in Section 2.2), that can handle any dataset that can also be handled by Iris, 'a powerful, format-agnostic, community-driven Python library for analysing and visualizing Earth science data' (Met Office, 2019). In practice, this restricts netCDF-SCM to handling CF-compliant datasets (details of CF-compliance available at http://cfconventions.org/Data/cf-conventions/cf-conventions-1.8/cf-conventions.html, last accessed: 25 June 2020). Having said that, netCDF-SCM is focussed on CMIP data and much of its value is based on the data reference syntax associated with CMIP output. The CMIP6 data reference syntax is available at github.com/WCRP-CMIP/CMIP6_CVs (last accessed: 25 June 2020), whilst the CMIP5 data reference syntax is available at https://pcmdi.llnl.gov/mips/cmip5/docs/cmip5_data_reference_syntax.pdf (last accessed: 25 June 2020).

Here, we comply with the CMIP5 and CMIP6 conditions of use by providing a summary of the data sources we have processed to date in Tables 1 and 2 and including the required acknowledgements statements. Tables 1 and 2 have been produced automatically from the source data using netCDF-SCM (documentation at netcdf-scm.readthedocs.io/en/latest/usage/using-cmip-data.html, last accessed 25 June 2020). In addition, we provide tools to check whether a dataset has been retracted (see Section 2.2.3). We hope this automation can be useful to other researchers too and enhances other existing CMIP6 functionality given our extensive efforts to follow 'CMIP6 data management and integrity objectives' (Balaji et al., 2018).

2.2 | Methods

In principle, our derived dataset is easy to produce. It consists of weighted means of different horizontal area sections of the raw data, which are then joined together to create timeseries which span both the historical and future scenario simulations. In practice, the collection, joining and processing of the huge data volumes turns it into a non-trivial effort.

To address this in an automated way, we have developed the netCDF-SCM package gitlab.com/netcdf-scm/netcdf-scm, available under the open source initiative approved BSD-3-Clause licence (see https://opensource.org/licenses and Morin et al. (2012) for more information on open source software licences for scientists). The netCDF-SCM package builds on the Iris package (Met Office, 2019) and relies heavily on the numerous capabilities Iris offers. We welcome the addition of new features to the netCDF-SCM package (its development is hosted at gitlab.com/netcdf-scm/netcdf-scm).

We have validated netCDF-SCM in a number of ways. Firstly, we have compared our global-mean calculations with the limited set of data available on the KNMI climate explorer (climexp.knmi.nl/start.cgi, last accessed 7th October 2020) and found them to be within 0.1% in all cases. Secondly, we have run an extensive test suite over the entire netCDF-SCM package (the test suite is run with every update to the software in a process known as 'continuous integration', see, e.g., https://about.gitlab.com/blog/2018/01/22/a-beginners-guide-to-continuous-integration/). This test suite includes unit tests (tests of individual bits of functionality in isolation from the rest of the package), integration tests (end-to-end tests of the behaviour of the package) and regression tests (tests of changes in outputs of the package compared to previous versions). Combined, these tests cover 98% of the codebase, with much of the package being run many times over as part of the testing process.

2.2.1 | Weighted means

We combine raw data, cell areas and cell surface fraction information to produce appropriately weighted means for each region of interest (Figure 1). We calculate the weighted means as follows:

$$v(r,t,\vec{Z}) = \frac{\sum_{\vec{Y}} X(t,\vec{Y},\vec{Z}) \times A(\vec{Y},\vec{Z}) \times f(r,\vec{Y},\vec{Z})}{\sum_{\vec{Y}} A(\vec{Y},\vec{Z}) \times f(r,\vec{Y},\vec{Z})} \quad (1)$$

TABLE 1 CMIP5 data used in this study

Modelling group	Climate model	Scenario	Reference
CCCMA	CanCM4	historical	Canadian Centre For Climate Modelling And Analysis (CCCma) (2015a)
		rcp45	Canadian Centre For Climate Modelling And Analysis (CCCma) (2015b)
CMCC	CMCC-CM	1pctCO2	Scoccimarro and Gualdi (2014a)
		historical	Scoccimarro and Gualdi (2014b)
	CMCC-CMS	historical	Centro Euro-Mediterraneo Sui Cambiamenti Climatici (CMCC) (2013a)
		rcp45	Centro Euro-Mediterraneo Sui Cambiamenti Climatici (CMCC) (2013b)
		rcp85	Centro Euro-Mediterraneo Sui Cambiamenti Climatici (CMCC) (2013c)
CNRM-CERFACS	CNRM-CM5	1pctCO2	Sénési et al. (2014a)
		abrupt4xCO2	Sénési et al. (2014b)
		esmFdbk1	Sénési et al. (2014c)
		historical	Sénési et al. (2014d)
		historicalExt	Sénési et al. (2014e)
		historicalGHG	Sénési et al. (2014f)
		historicalMisc	Sénési et al. (2014g)
		historicalNat	Sénési et al. (2014h)
		piControl	Sénési et al. (2014i)
		rcp26	Sénési et al. (2014j)
		rcp45	Sénési et al. (2014k)
		rcp85	Sénési et al. (2014l)
FIO	FIO-ESM	historical	Qiao et al. (2013a)
		rcp26	Qiao et al. (2013b)
		rcp45	Qiao et al. (2013c)
		rcp60	Qiao et al. (2013d)
		rcp85	Qiao et al. (2013e)
GCESS	BNU-ESM	1pctCO2	Ji et al. (2015a)
		abrupt4xCO2	Ji et al. (2015b)
		amip	Ji et al. (2015c)
		historical	Ji et al. (2015d)
		historicalGHG	Ji et al. (2015e)
		historicalMisc	Ji et al. (2015f)
		historicalNat	Ji et al. (2015g)
		piControl	Ji et al. (2015h)
		rcp26	Ji et al. (2015i)
		rcp45	Ji et al. (2015j)
		rcp85	Ji et al. (2015k)
IPSL	IPSL-CM5A-LR	1pctCO2	Caubel et al. (2016a)
		abrupt4xCO2	Foujols et al. (2016a)
		esmFdbk1	Foujols et al. (2016b)
		esmFixClim2	Bopp et al. (2016)
		Historical	Denvil et al. (2016a)
		historicalGHG	Caubel et al. (2016b)
		historicalMisc	Caubel et al. (2016c)
		historicalNat	Caubel et al. (2016d)
		piControl	Caubel et al. (2016e)

(Continues)

TABLE 1 (Continued)

Modelling group	Climate model	Scenario	Reference
		rcp26	Denvil et al. (2016b)
		rcp45	Denvil et al. (2016c)
		rcp60	Denvil et al. (2016d)
		rcp85	Denvil et al. (2016e)
LASG-CESS	FGOALS-g2	1pctCO2	LASG, Institute Of Atmospheric Physics, Chinese Academy Of Sciences (IAP-LASG) (2015a)
		abrupt4xCO2	LASG, Institute Of Atmospheric Physics, Chinese Academy Of Sciences (IAP-LASG) (2015b)
		historical	LASG, Institute Of Atmospheric Physics, Chinese Academy Of Sciences (IAP-LASG) (2015c)
		historicalGHG	LASG, Institute Of Atmospheric Physics, Chinese Academy Of Sciences (IAP-LASG) (2015d)
		historicalMisc	LASG, Institute Of Atmospheric Physics, Chinese Academy Of Sciences (IAP-LASG) (2015e)
		historicalNat	LASG, Institute Of Atmospheric Physics, Chinese Academy Of Sciences (IAP-LASG) (2015f)
		piControl	LASG, Institute Of Atmospheric Physics, Chinese Academy Of Sciences (IAP-LASG) (2015g)
		rcp26	LASG, Institute Of Atmospheric Physics, Chinese Academy Of Sciences (IAP-LASG) (2015h)
		rcp45	LASG, Institute Of Atmospheric Physics, Chinese Academy Of Sciences (IAP-LASG) (2015i)
		rcp85	LASG, Institute Of Atmospheric Physics, Chinese Academy Of Sciences (IAP-LASG) (2015j)
MIROC	MIROC-ESM	1pctCO2	Japan Agency For Marine-Earth Science And Technology (JAM- STEC) et al. (2015a)
		abrupt4xCO2	Japan Agency For Marine-Earth Science And Technology (JAM- STEC) et al. (2015b)
		esmFixClim2	Japan Agency For Marine-Earth Science And Technology (JAM- STEC) et al. (2015c)
		esmHistorical	Japan Agency For Marine-Earth Science And Technology (JAM- STEC) et al. (2015d)
		esmrcp85	Japan Agency For Marine-Earth Science And Technology (JAM- STEC) et al. (2015e)
		historical	Japan Agency For Marine-Earth Science And Technology (JAM- STEC) et al. (2015f)
		historicalGHG	Japan Agency For Marine-Earth Science And Technology (JAM- STEC) et al. (2015g)
		historicalNat	Japan Agency For Marine-Earth Science And Technology (JAM- STEC) et al. (2015h)
		piControl	Japan Agency For Marine-Earth Science And Technology (JAM- STEC) et al. (2015i)
		rcp26	Japan Agency For Marine-Earth Science And Technology (JAM- STEC) et al. (2015j)
		rcp45	Japan Agency For Marine-Earth Science And Technology (JAM- STEC) et al. (2015k)
		rcp60	Japan Agency For Marine-Earth Science And Technology (JAM- STEC) et al. (2015l)

(Continues)

TABLE 1 (Continued)

Modelling group	Climate model	Scenario	Reference
		rcp85	Japan Agency For Marine-Earth Science And Technology (JAM- STEC) et al. (2015m)
MOHC	HadGEM2-ES	abrupt4xCO2	Webb et al. (2014)
MPI-M	MPI-ESM-LR	1pctCO2	Giorgetta et al. (2012a)
		abrupt4xCO2	Giorgetta et al. (2012b)
		esmFdbk1	Reick et al. (2012)
		historical	Giorgetta et al. (2012c)
		piControl	Giorgetta et al. (2012d)
		rcp26	Giorgetta et al. (2012e)
		rcp45	Giorgetta et al. (2012f)
		rcp85	Giorgetta et al. (2012g)
NASA GISS	GISS-E2-H	1pctCO2	NASA Goddard Institute For Space Studies (NASA/GISS) (2014a)
		abrupt4xCO2	NASA Goddard Institute For Space Studies (NASA/GISS) (2014b)
		historical	NASA Goddard Institute For Space Studies (NASA/GISS) (2014c)
		historicalExt	NASA Goddard Institute For Space Studies (NASA/GISS) (2014d)
		historicalGHG	NASA Goddard Institute For Space Studies (NASA/GISS) (2014e)
		historicalMisc	NASA Goddard Institute For Space Studies (NASA/GISS) (2014f)
		historicalNat	NASA Goddard Institute For Space Studies (NASA/GISS) (2014g)
		piControl	NASA Goddard Institute For Space Studies (NASA/GISS) (2014h)
		rcp26	NASA Goddard Institute For Space Studies (NASA/GISS) (2014i)
		rcp45	NASA Goddard Institute For Space Studies (NASA/GISS) (2014j)
		rcp60	NASA Goddard Institute For Space Studies (NASA/GISS) (2014k)
		rcp85	NASA Goddard Institute For Space Studies (NASA/GISS) (2014l)
NCAR	CCSM4	1pctCO2	Meehl (2014i)
		abrupt4xCO2	Meehl (2014j)
		historical	Meehl (2014a)
		historicalGHG	Meehl (2014h)
		historicalMisc	Meehl (2014f)
		historicalNat	Meehl (2014g)
		piControl	Gent (2014)
		rcp26	Meehl (2014b)
		rcp45	Meehl (2014c)
		rcp60	Meehl (2014d)
		rcp85	Meehl (2014e)
NCC	NorESM1-M	1pctCO2	Bentsen et al. (2012a)
		abrupt4xCO2	Bentsen et al. (2012b)
		amip	Bentsen et al. (2012c)
		historical	Bentsen et al. (2012d)
		historicalExt	Bentsen et al. (2012e)
		historicalGHG	Bentsen et al. (2012f)
		historicalMisc	Bentsen et al. (2012g)
		historicalNat	Bentsen et al. (2012h)
		piControl	Bentsen et al. (2011)
		rcp26	Bentsen et al. (2012i)

(Continues)

TABLE 1 (Continued)

Modelling group	Climate model	Scenario	Reference
		rcp45	Bentsen et al. (2012j)
		rcp60	Bentsen et al. (2012k)
		rcp85	Bentsen et al. (2012l)
NOAA GFDL	GFDL-CM3	1pctCO2	Horowitz et al. (2014a)
		abrupt4xCO2	Horowitz et al. (2014b)
		historical	Horowitz et al. (2014c)
		historicalGHG	Horowitz et al. (2014d)
		historicalMisc	Horowitz et al. (2014e)
		historicalNat	Horowitz et al. (2014f)
		rcp26	Horowitz et al. (2014g)
		rcp45	Horowitz et al. (2014h)
		rcp60	Horowitz et al. (2014i)
		rcp85	Horowitz et al. (2014j)
	GFDL-ESM2G	1pctCO2	Dunne et al. (2014a)
		historicalMisc	Dunne et al. (2014b)
	GFDL-ESM2M	1pctCO2	Dunne et al. (2014c)
		historicalGHG	Dunne et al. (2014d)
		historicalMisc	Dunne et al. (2014e)
		historicalNat	Dunne et al. (2014f)

where $v(r, t, \vec{Z})$ is the output for horizontal region of interest r at time t and non-horizontal spatial coordinate vector $\vec{Z}$, $\vec{Y}$ is the horizontal spatial coordinate of each cell, $X(t, \vec{Y}, \vec{Z})$ is the raw data at time t in the cell with horizontal spatial coordinate vector $\vec{Y}$ and non-horizontal spatial coordinate vector $\vec{Z}$, $A(\vec{Y}, \vec{Z})$ is the horizontal area of the cell, and $f(r, \vec{Y}, \vec{Z})$ is the relevant surface fraction of the cell for the region of interest. Here, 'horizontal region' refers to a region defined by latitude and longitude only.

The cell area and surface fractions specific to the climate model of interest are determined using the CMIP data reference syntax and the CMIP output metadata. If the cell area and/or surface fraction information is not available, netCDF-SCM will simply use inbuilt best-guess cell areas and surface fractions. The best-guesses cell areas use Iris' (MetOffice, 2019) functionality to calculate cell areas based on each cell's bounds (cell areas are calculated as $r^2(lon_1 - lon_0) * (\sin(lat_1) - \sin(lat_0))$, where r is the Earth's radius, lon_1 and lon_0 are the longitude (east–west) bounds of the cell, and lat_1 and lat_0 are the latitude (north–south) bounds of the cell). The best-guess surface fractions are the result of interpolating the surface fractions from *IPSL-CM6A-LR* climate model historical simulations (Boucher et al., 2018g) onto a regular 1 × 1 grid. When calculating weighted averages, these best-guess surface fractions are then interpolated onto the model of interest's grid. This process works best with data on a regular grid. Given their complexity, on some models' native grids it may be necessary to obtain the cell area and surface fraction information before the data can be processed. We have examined the importance of the choice of best-guess surface fractions and found that basing our best-guess surface fractions on other climate models would make a negligible difference (<1%) to our results. In cases where the cell area and surface fraction are particularly important (e.g. for small regions), we stress that the most accurate results can only be obtained by using the cell area and surface fractions specific to the climate model of interest.

We also ensure that we use the surface fractions appropriate to the domain of the data of interest (f in Equation (1)). For atmospheric data, we simply use surface land fractions for land regions and surface ocean fractions for ocean regions. For land- and ocean-specific data, more care is required because there are two different options. Assume we're considering land-specific data. The first option is to include the land surface fractions in the weights. This choice means that each cell is weighted by the area of land in the cell, not by the total area of the cell. The second is to only consider whether any of the cell is land. If any of the cell is land, then we set f in Equation (1) equal to one; otherwise, we set f equal to zero otherwise. This choice means that each cell is weighted by the total area of the cell, unless it is not land at all in which case it receives zero weight. The same logic can be applied to ocean-specific data, using ocean fractions instead of land fractions as required.

For land data, for example data from C4MIP (Jones et al., 2016), we use the first option; that is, we weight by area and

TABLE 2 CMIP6 data used in this study

Modelling Group	Climate Model	Scenario	Reference
AWI	AWI-CM-1-1-MR	1pctCO2	Semmler et al. (2018c)
		abrupt-4xCO2	Semmler et al. (2018d)
		historical	Semmler et al. (2018e)
		piControl	Semmler et al. (2018f)
		ssp126	Semmler et al. (2018a)
		ssp245	Semmler et al. (2018b)
		ssp370	Semmler et al. (2019a)
		ssp585	Semmler et al. (2019b)
	AWI-ESM-1-1-LR	historical	Danek et al. (2020)
BCC	BCC-CSM2-MR	1pctCO2	Wu et al. (2018a)
		1pctCO2-bgc	Wu et al. (2019a)
		1pctCO2-rad	Wu et al. (2019b)
		abrupt-4xCO2	Wu et al. (2018b)
		esm-hist	Wu et al. (2018c)
		esm-piControl	Wu et al. (2018d)
		esm-ssp585	Wu et al. (2019c)
		hist-GHG	Wu et al. (2019e)
		hist-aer	Wu et al. (2019d)
		hist-nat	Wu et al. (2019f)
		historical	Wu et al. (2018e)
		piControl	Wu et al. (2018f)
		ssp126	Xin et al. (2019a)
		ssp245	Xin et al. (2019b)
		ssp370	Xin et al. (2019c)
		ssp585	Xin et al. (2019d)
	BCC-ESM1	1pctCO2	Zhang et al. (2019c)
		abrupt-4xCO2	Zhang et al. (2019d)
		historical	Zhang et al. (2018a)
		piControl	Zhang et al. (2018b)
		ssp370	Zhang et al. (2019b)
		ssp370-lowNTCF	Zhang et al. (2019a)
CAMS	CAMS-CSM1-0	1pctCO2	Rong (2019a)
		abrupt-4xCO2	Rong (2019b)
		historical	Rong (2019c)
		piControl	Rong (2019d)
CAS	CAS-ESM2-0	1pctCO2	Chai (2020c)
		abrupt-4xCO2	Chai (2020d)
		historical	Chai (2020a)
		piControl	Chai (2020b)
	FGOALS-f3-L	1pctCO2	Yu (2019a)
		abrupt-4xCO2	Yu (2019b)
		historical	Yu (2019c)
		piControl	Yu (2019d)

(Continues)

TABLE 2 (Continued)

Modelling Group	Climate Model	Scenario	Reference
CCCR-IITM	IITM-ESM	1pctCO2	Raghavan and Panickal (2019a)
		piControl	Raghavan and Panickal (2019b)
CCCma	CanESM5	1pctCO2	Swart et al. (2019h)
		1pctCO2-bgc	Swart et al. (2019e)
		1pctCO2-rad	Swart et al. (2019f)
		abrupt-2xCO2	Cole et al. (2019)
		abrupt-4xCO2	Swart et al. (2019i)
		esm-hist	Swart et al. (2019j)
		esm-piControl	Swart et al. (2019k)
		esm-ssp585	Swart et al. (2019g)
		hist-GHG	Swart et al. (2019o)
		hist-aer	Swart et al. (2019n)
		hist-nat	Swart et al. (2019p)
		hist-stratO3	Swart et al. (2019q)
		historical	Swart et al. (2019l)
		piControl	Swart et al. (2019m)
		ssp119	Swart et al. (2019s)
		ssp126	Swart et al. (2019t)
		ssp245	Swart et al. (2019u)
		ssp245-nat	Swart et al. (2019r)
		ssp370	Swart et al. (2019v)
		ssp434	Swart et al. (2019w)
		ssp460	Swart et al. (2019x)
		ssp534-over	Swart et al. (2019y)
		ssp585	Swart et al. (2019z)
	CanESM5-CanOE	1pctCO2	Swart et al. (2019b)
		esm-hist	Swart et al. (2019c)
		esm-ssp585	Swart et al. (2019a)
		historical	Swart et al. (2019d)
		piControl	Swart et al. (2019aa)
		ssp126	Swart et al. (2019ab)
		ssp245	Swart et al. (2019ac)
		ssp370	Swart et al. (2019ad)
		ssp585	Swart et al. (2019ae)
CNRM-CERFACS	CNRM-CM6-1	1pctCO2	Voldoire (2018a)
		abrupt-0p5xCO2	Voldoire (2019g)
		abrupt-2xCO2	Voldoire (2019h)
		abrupt-4xCO2	Voldoire (2018b)
		hist-GHG	Voldoire (2019j)
		hist-aer	Voldoire (2019i)
		hist-nat	Voldoire (2019k)
		historical	Voldoire (2018c)
		piControl	Voldoire (2018d)
		ssp126	Voldoire (2019l)

(Continues)

TABLE 2 (Continued)

Modelling Group	Climate Model	Scenario	Reference
		ssp245	Voldoire (2019m)
		ssp370	Voldoire (2019n)
		ssp585	Voldoire (2019o)
	CNRM-CM6-1-HR	1pctCO2	Voldoire (2019a)
		abrupt-4xCO2	Voldoire (2019b)
		historical	Voldoire (2019c)
		piControl	Voldoire (2019d)
		ssp126	Voldoire (2020a)
		ssp245	Voldoire (2019e)
		ssp370	Voldoire (2020b)
		ssp585	Voldoire (2019f)
	CNRM-ESM2-1	1pctCO2	Seferian (2018c)
		1pctCO2-bgc	Seferian (2018a)
		1pctCO2-rad	Seferian (2018b)
		abrupt-4xCO2	Seferian (2018d)
		esm-hist	Seferian (2019b)
		esm-piControl	Seferian (2019c)
		historical	Seferian (2018e)
		piControl	Seferian (2018f)
		ssp119	Voldoire (2019p)
		ssp126	Voldoire (2019q)
		ssp245	Voldoire (2019r)
		ssp370	Voldoire (2019s)
		ssp370-lowNTCF	Seferian (2019a)
		ssp434	Voldoire (2019t)
		ssp460	Voldoire (2019u)
		ssp534-over	Voldoire (2019v)
		ssp585	Voldoire (2019w)
CSIRO	ACCESS-ESM1-5	1pctCO2	Ziehn et al. (2019g)
		1pctCO2-bgc	Ziehn et al. (2019a)
		1pctCO2-rad	Ziehn et al. (2019b)
		abrupt-4xCO2	Ziehn et al. (2019h)
		esm-1pct-brch-1000PgC	Ziehn et al. (2019c)
		esm-1pct-brch-2000PgC	Ziehn et al. (2019d)
		esm-1pct-brch-750PgC	Ziehn et al. (2019e)
		esm-hist	Ziehn et al. (2019i)
		esm-piControl	Ziehn et al. (2019j)
		esm-ssp585	Ziehn et al. (2019f)
		historical	Ziehn et al. (2019k)
		piControl	Ziehn et al. (2019l)
		ssp126	Ziehn et al. (2019m)
		ssp245	Ziehn et al. (2019n)
		ssp370	Ziehn et al. (2019o)
		ssp585	Ziehn et al. (2019p)

(Continues)

TABLE 2 (Continued)

Modelling Group	Climate Model	Scenario	Reference
CSIRO-ARCCSS	ACCESS-CM2	1pctCO2	Dix et al. (2019a)
		abrupt-4xCO2	Dix et al. (2019b)
		historical	Dix et al. (2019c)
		piControl	Dix et al. (2019d)
		ssp126	Dix et al. (2019e)
		ssp245	Dix et al. (2019f)
		ssp370	Dix et al. (2019g)
		ssp585	Dix et al. (2019h)
E3SM-Project	E3SM-1-0	1pctCO2	Bader et al. (2019a)
		abrupt-4xCO2	Bader et al. (2019b)
		historical	Bader et al. (2019c)
		piControl	Bader et al. (2018)
		historical	Bader et al. (2019d)
		piControl	Bader et al. (2019e)
	E3SM-1-1-ECA	historical	Bader et al. (2020)
		piControl	Bader et al. (2019f)
EC-Earth-Consortium	EC-Earth3	1pctCO2	EC-Earth Consortium (EC-Earth) (2019b)
		abrupt-4xCO2	EC-Earth Consortium (EC-Earth) (2019c)
		historical	EC-Earth Consortium (EC-Earth) (2019d)
		piControl	EC-Earth Consortium (EC-Earth) (2019e)
		ssp119	EC-Earth Consortium (EC-Earth) (2019f)
		ssp126	EC-Earth Consortium (EC-Earth) (2019g)
		ssp245	EC-Earth Consortium (EC-Earth) (2019h)
		ssp585	EC-Earth Consortium (EC-Earth) (2019i)
	EC-Earth3-LR	piControl	EC-Earth Consortium (EC-Earth) (2019a)
	EC-Earth3-Veg	1pctCO2	EC-Earth Consortium (EC-Earth) (2019j)
		abrupt-4xCO2	EC-Earth Consortium (EC-Earth) (2019k)
		historical	EC-Earth Consortium (EC-Earth) (2019l)
		piControl	EC-Earth Consortium (EC-Earth) (2019m)
		ssp119	EC-Earth Consortium (EC-Earth) (2019n)
		ssp126	EC-Earth Consortium (EC-Earth) (2019o)
		ssp245	EC-Earth Consortium (EC-Earth) (2019p)
		ssp370	EC-Earth Consortium (EC-Earth) (2019q)
		ssp585	EC-Earth Consortium (EC-Earth) (2019r)
	EC-Earth3-Veg-LR	historical	EC-Earth Consortium (EC-Earth) (2020a)
		piControl	EC-Earth Consortium (EC-Earth) (2020b)
FIO-QLNM	FIO-ESM-2-0	1pctCO2	Song et al. (2020a)
		abrupt-4xCO2	Song et al. (2020b)
		historical	Song et al. (2019a)
		piControl	Song et al. (2019b)
IPSL	IPSL-CM6A-LR	1pctCO2	Boucher et al. (2018e)
		1pctCO2-bgc	Boucher et al. (2018a)
		1pctCO2-rad	Boucher et al. (2018b)
		abrupt-0p5xCO2	Boucher et al. (2018c)

(Continues)

TABLE 2 (Continued)

Modelling Group	Climate Model	Scenario	Reference
		abrupt-2xCO2	Boucher et al. (2018d)
		abrupt-4xCO2	Boucher et al. (2018f)
		hist-GHG	Boucher et al. (2018j)
		hist-aer	Boucher et al. (2018i)
		hist-nat	Boucher et al. (2018k)
		hist-stratO3	Boucher et al. (2018l)
		historical	Boucher et al. (2018g)
		piControl	Boucher et al. (2018h)
		ssp119	Boucher et al. (2019a)
		ssp126	Boucher et al. (2019b)
		ssp245	Boucher et al. (2019c)
		ssp370	Boucher et al. (2019d)
		ssp434	Boucher et al. (2019e)
		ssp460	Boucher et al. (2019f)
		ssp534-over	Boucher et al. (2019g)
		ssp585	Boucher et al. (2019h)
MIROC	MIROC-ES2L	1pctCO2	Hajima et al. (2019a)
		1pctCO2-bgc	Hajima et al. (2019e)
		1pctCO2-rad	Hajima et al. (2019f)
		abrupt-4xCO2	Hajima et al. (2019b)
		esm-hist	Hajima et al. (2020a)
		esm-piControl	Hajima et al. (2020b)
		historical	Hajima et al. (2019c)
		piControl	Hajima et al. (2019d)
		ssp119	Tachiiri et al. (2019a)
		ssp126	Tachiiri et al. (2019b)
		ssp245	Tachiiri et al. (2019c)
		ssp370	Tachiiri et al. (2019d)
		ssp585	Tachiiri et al. (2019e)
	MIROC6	1pctCO2	Tatebe and Watanabe (2018a)
		abrupt-0p5xCO2	Ogura et al. (2019a)
		abrupt-2xCO2	Ogura et al. (2019b)
		abrupt-4xCO2	Tatebe and Watanabe (2018b)
		hist-GHG	Shiogama (2019b)
		hist-aer	Shiogama (2019a)
		hist-nat	Shiogama (2019c)
		hist-stratO3	Shiogama (2019d)
		historical	Tatebe and Watanabe (2018c)
		piControl	Tatebe and Watanabe (2018d)
		ssp119	Shiogama et al. (2019a)
		ssp126	Shiogama et al. (2019b)
		ssp245	Shiogama et al. (2019c)
		ssp245-nat	Shiogama (2019e)
		ssp370	Shiogama et al. (2019d)

(Continues)

TABLE 2 (Continued)

Modelling Group	Climate Model	Scenario	Reference
		ssp370-lowNTCF	Takemura (2019)
		ssp434	Shiogama et al. (2019e)
		ssp460	Shiogama et al. (2019f)
		ssp534-over	Shiogama et al. (2019g)
		ssp585	Shiogama et al. (2019h)
MOHC	HadGEM3-GC31-LL	1pctCO2	Ridley et al. (2019a)
		abrupt-4xCO2	Ridley et al. (2019b)
		hist-GHG	Jones (2019g)
		hist-aer	Jones (2019f)
		hist-nat	Jones (2019h)
		historical	Ridley et al. (2019c)
		piControl	Ridley et al. (2018)
		ssp126	Good (2020a)
		ssp245	Good (2019)
		ssp585	Good (2020b)
	HadGEM3-GC31-MM	1pctCO2	Ridley et al. (2020a)
		abrupt-4xCO2	Ridley et al. (2020b)
		historical	Ridley et al. (2019d)
		piControl	Ridley et al. (2019e)
	UKESM1-0-LL	1pctCO2	Tang et al. (2019a)
		1pctCO2-bgc	Jones (2019a)
		1pctCO2-rad	Jones (2019b)
		abrupt-4xCO2	Tang et al. (2019b)
		esm-1pct-brch-1000PgC	Jones (2020a)
		esm-1pct-brch-2000PgC	Jones (2019c)
		esm-1pct-brch-750PgC	Jones (2019d)
		esm-hist	Tang et al. (2019c)
		esm-piControl	Tang et al. (2019d)
		esm-ssp534-over	Jones et al. (2020)
		esm-ssp585	Jones (2019e)
		historical	Tang et al. (2019e)
		piControl	Tang et al. (2019f)
		ssp119	Good et al. (2019a)
		ssp126	Good et al. (2019b)
		ssp245	Good et al. (2019c)
		ssp370	Good et al. (2019d)
		ssp434	Good et al. (2019e)
		ssp534-over	Good et al. (2019f)
		ssp585	Good et al. (2019g)
MPI-M	MPI-ESM1-2-HR	1pctCO2	Jungclaus et al. (2019a)
		abrupt-4xCO2	Jungclaus et al. (2019b)
		historical	Jungclaus et al. (2019c)
		piControl	Jungclaus et al. (2019d)
	MPI-ESM1-2-LR	1pctCO2	Wieners et al. (2019e)

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TABLE 2 (Continued)

Modelling Group	Climate Model	Scenario	Reference
		1pctCO2-bgc	Brovkin et al. (2019a)
		1pctCO2-rad	Brovkin et al. (2019b)
		abrupt-4xCO2	Wieners et al. (2019f)
		esm-hist	Wieners et al. (2019g)
		esm-piControl	Wieners et al. (2019h)
		esm-ssp585	Brovkin et al. (2019c)
		historical	Wieners et al. (2019i)
		piControl	Wieners et al. (2019j)
		ssp126	Wieners et al. (2019a)
		ssp245	Wieners et al. (2019b)
		ssp370	Wieners et al. (2019c)
		ssp585	Wieners et al. (2019d)
MRI	MRI-ESM2-0	1pctCO2	Yukimoto et al. (2019e)
		1pctCO2-bgc	Yukimoto et al. (2019b)
		1pctCO2-rad	Yukimoto et al. (2019c)
		abrupt-0p5xCO2	Yukimoto et al. (2020a)
		abrupt-2xCO2	Yukimoto et al. (2020b)
		abrupt-4xCO2	Yukimoto et al. (2019f)
		esm-hist	Yukimoto et al. (2019g)
		esm-piControl	Yukimoto et al. (2019h)
		esm-ssp585	Yukimoto et al. (2019d)
		hist-GHG	Yukimoto et al. (2019l)
		hist-aer	Yukimoto et al. (2019k)
		hist-nat	Yukimoto et al. (2019m)
		hist-stratO3	Yukimoto et al. (2020c)
		historical	Yukimoto et al. (2019i)
		piControl	Yukimoto et al. (2019j)
		ssp119	Yukimoto et al. (2019n)
		ssp126	Yukimoto et al. (2019o)
		ssp245	Yukimoto et al. (2019p)
		ssp370	Yukimoto et al. (2019q)
		ssp370-lowNTCF	Yukimoto et al. (2019a)
		ssp434	Yukimoto et al. (2019r)
		ssp460	Yukimoto et al. (2019s)
		ssp534-over	Yukimoto et al. (2019t)
		ssp585	Yukimoto et al. (2019u)
NASA-GISS	GISS-E2-1-G	1pctCO2	NASA Goddard Institute For Space Studies (NASA/GISS) (2018b)
		1pctCO2-bgc	NASA Goddard Institute For Space Studies (NASA/GISS) (2019h)
		1pctCO2-rad	NASA Goddard Institute For Space Studies (NASA/GISS) (2019i)
		abrupt-0p5xCO2	NASA Goddard Institute For Space Studies (NASA/GISS) (2019j)
		abrupt-2xCO2	NASA Goddard Institute For Space Studies (NASA/GISS) (2018a)
		abrupt-4xCO2	NASA Goddard Institute For Space Studies (NASA/GISS) (2018c)
		hist-GHG	NASA Goddard Institute For Space Studies (NASA/GISS) (2018g)
		hist-aer	NASA Goddard Institute For Space Studies (NASA/GISS) (2018f)

(Continues)

TABLE 2 (Continued)

Modelling Group	Climate Model	Scenario	Reference
		hist-nat	NASA Goddard Institute For Space Studies (NASA/GISS) (2018h)
		historical	NASA Goddard Institute For Space Studies (NASA/GISS) (2018d)
		piControl	NASA Goddard Institute For Space Studies (NASA/GISS) (2018e)
		ssp245	NASA Goddard Institute For Space Studies (NASA/GISS) (2020a)
		ssp370	NASA Goddard Institute For Space Studies (NASA/GISS) (2020b)
		ssp585	NASA Goddard Institute For Space Studies (NASA/GISS) (2020c)
	GISS-E2-1-G-CC	esm-1pctCO2	NASAGoddard Institute For Space Studies (NASA/GISS) (2019a)
		historical	NASA Goddard Institute For Space Studies (NASA/GISS) (2019b)
		piControl	NASA Goddard Institute For Space Studies (NASA/GISS) (2019c)
	GISS-E2-1-H	1pctCO2	NASA Goddard Institute For Space Studies (NASA/GISS) (2019l)
		abrupt-2xCO2	NASA Goddard Institute For Space Studies (NASA/GISS) (2019k)
		abrupt-4xCO2	NASA Goddard Institute For Space Studies (NASA/GISS) (2019m)
		historical	NASA Goddard Institute For Space Studies (NASA/GISS) (2019n)
		piControl	NASA Goddard Institute For Space Studies (NASA/GISS) (2018i)
	GISS-E2-2-G	1pctCO2	NASA Goddard Institute For Space Studies (NASA/GISS) (2019e)
		abrupt-2xCO2	NASA Goddard Institute For Space Studies (NASA/GISS) (2019d)
		abrupt-4xCO2	NASA Goddard Institute For Space Studies (NASA/GISS) (2019f)
		piControl	NASA Goddard Institute For Space Studies (NASA/GISS) (2019g)
NCAR	CESM2	1pctCO2	Danabasoglu (2019d)
		1pctCO2-bgc	Danabasoglu (2019c)
		abrupt-0p5xCO2	Danabasoglu (2020c)
		abrupt-2xCO2	Danabasoglu (2020d)
		abrupt-4xCO2	Danabasoglu (2019e)
		esm-hist	Danabasoglu (2019f)
		esm-piControl	Danabasoglu (2019g)
		hist-GHG	Danabasoglu (2019i)
		hist-aer	Danabasoglu (2020e)
		hist-nat	Danabasoglu (2019j)
		historical	Danabasoglu (2019h)
		piControl	Danabasoglu et al. (2019)
		ssp126	Danabasoglu (2019k)
		ssp245	Danabasoglu (2019l)
		ssp245-nat	Danabasoglu (2020f)
		ssp370	Danabasoglu (2019m)
		ssp585	Danabasoglu (2019n)
	CESM2-FV2	1pctCO2	Danabasoglu (2020a)
		abrupt-4xCO2	Danabasoglu (2020b)
		historical	Danabasoglu (2019a)
		piControl	Danabasoglu (2019b)
	CESM2-WACCM	1pctCO2	Danabasoglu (2019r)
		abrupt-4xCO2	Danabasoglu (2019s)
		historical	Danabasoglu (2019t)
		piControl	Danabasoglu (2019u)
		ssp126	Danabasoglu (2019v)

(Continues)

TABLE 2 (Continued)

Modelling Group	Climate Model	Scenario	Reference
		ssp245	Danabasoglu (2019w)
		ssp370	Danabasoglu (2019x)
		ssp370-lowNTCF	Danabasoglu (2019q)
		ssp534-over	Danabasoglu (2019y)
		ssp585	Danabasoglu (2019z)
	CESM2-WACCM-FV2	1pctCO2	Danabasoglu (2020g)
		abrupt-4xCO2	Danabasoglu (2020h)
		historical	Danabasoglu (2019o)
		piControl	Danabasoglu (2019p)
NCC	NorCPM1	1pctCO2	Bethke et al. (2019a)
		abrupt-4xCO2	Bethke et al. (2019b)
		historical	Bethke et al. (2019c)
		piControl	Bethke et al. (2019d)
	NorESM1-F	piControl	Guo et al. (2019)
	NorESM2-LM	1pctCO2	Seland et al. (2019a)
		1pctCO2-rad	Schwinger et al. (2020)
		abrupt-4xCO2	Seland et al. (2019b)
		esm-1pct-brch-1000PgC	Schwinger et al. (2019)
		esm-hist	Seland et al. (2019c)
		esm-piControl	Seland et al. (2019d)
		hist-GHG	Seland et al. (2019h)
		hist-aer	Seland et al. (2019g)
		hist-nat	Seland et al. (2019i)
		historical	Seland et al. (2019e)
		piControl	Seland et al. (2019f)
	NorESM2-MM	1pctCO2	Bentsen et al. (2019a)
		abrupt-4xCO2	Bentsen et al. (2019b)
		historical	Bentsen et al. (2019c)
		piControl	Bentsen et al. (2019d)
NIMS-KMA	KACE-1-0-G	historical	Byun et al. (2019)
	UKESM1-0-LL	historical	Byun (2020)
NOAA-GFDL	GFDL-CM4	1pctCO2	Guo et al. (2018a)
		abrupt-4xCO2	Guo et al. (2018b)
		historical	Guo et al. (2018c)
		piControl	Guo et al. (2018d)
	GFDL-ESM4	1pctCO2	Krasting et al. (2018d)
		1pctCO2-bgc	Krasting et al. (2018a)
		1pctCO2-rad	Krasting et al. (2018b)
		abrupt-4xCO2	Krasting et al. (2018e)
		esm-hist	Krasting et al. (2018f)
		esm-piControl	Krasting et al. (2018g)
		esm-ssp585	Krasting et al. (2018c)
		hist-GHG	Horowitz et al. (2018b)
		hist-aer	Horowitz et al. (2018a)

(Continues)

TABLE 2 (Continued)

Modelling Group	Climate Model	Scenario	Reference
		hist-nat	Horowitz et al. (2018c)
		historical	Krasting et al. (2018h)
		piControl	Krasting et al. (2018i)
		ssp119	John et al. (2018a)
		ssp126	John et al. (2018b)
		ssp245	John et al. (2018e)
		ssp370	John et al. (2018c)
		ssp585	John et al. (2018d)
NUIST	NESM3	1pctCO2	Cao and Wang (2019a)
		abrupt-4xCO2	Cao and Wang (2019b)
		historical	Cao and Wang (2019c)
		piControl	Cao and Wang (2019d)
SNU	SAM0-UNICON	1pctCO2	Park and Shin (2019a)
		abrupt-4xCO2	Park and Shin (2019b)
		historical	Park and Shin (2019c)
		piControl	Park and Shin (2019d)
THU	CIESM	1pctCO2	Huang (2020a)
		abrupt-4xCO2	Huang (2020b)
		historical	Huang (2019a)
		piControl	Huang (2019b)
		ssp126	Huang (2019c)
		ssp585	Huang (2020c)

surface land fractions in our calculations. These surface fraction weights are important to apply because 'you do need to weight the output by land frac (sftlf is the CMIP variable name)' (Jones, 2020b) personalcomm in order to calculate weighted means correctly. In contrast, for ocean data we use the second option; that is, we weight only by area, having first assigned a weight of zero to any cells, which do not contain any ocean. We must apply this logic because ocean-specific data are given with respect to the horizontal area of the entire cell, not the horizontal area of ocean in the cell (Griffies et al., 2016).

This step is the most computationally expensive step. Being built on Iris (Met Office, 2019), netCDF-SCM is able to handle large datasets, largely thanks to the dask package (Dask Development Team, 2016). With parallel processing and user-defined memory usage settings, netCDF-SCM is able to be run on personal computers as well as cloud high performance computing infrastructures.

2.2.2 | Stitching experiments

CMIP data typically come in a 'family' of experiments, with each experiment having a 'parent' experiment and potentially 'children', 'grandchildren', 'great-grandchildren', etc. Each 'generation' can be joined with the previous to make a longer, continuous timeseries.

An obvious example of this is the ScenarioMIP (O'Neill et al., 2016) experiments. ScenarioMIP includes simulations of future scenarios. In order to create a complete timeseries from pre-industrial times through to the future, the scenario simulations must be joined with the historical simulations (their parent experiment) and the pre-industrial control (piControl) simulations. The need for joining experiments in this way, or 'stitching' them, appears beyond scenario simulations too. For example, many ZECMIP (Jones et al., 2019) experiments are the children of the one per cent per year increase in atmospheric CO2 concentration experiments (1pctCO2).

Stitching experiments together back to pre-industrial control runs requires a number of steps (Algorithm 1). It is necessary to combine the metadata provided in each file with the data reference syntax to efficiently traverse the data archive to find each relevant output. Then, the branch times in each experiment must be checked and aligned to ensure that the continuous timeseries is as intended. For full provenance, the metadata from each generation that has contributed to the 'stitched' output should also be preserved. Performing these steps is another one of netCDF-SCM's key functions, leading to continuous stitched outputs with complete metadata of all datasets, which have been used to make that output.

Algorithm 1 *Algorithm for stitching and normalizing. This algorithm does two things. Firstly, it joins together experiments which form a continuous sequence (e.g. a scenario-based experiment, which continues from a historical experiment). Secondly, it can, if desired, normalize experiments against pre-industrial control values. This allows users to, for example, calculate deviations from the background state or remove model drift from their output timeseries.*

```
load data
repeat
   find parent data
   align branch times in child and parent
   stitch onto existing data
   update metadata to keep track of ancestry
until parent is piControl or esm-piControl
if data should be normalised then
   determine branch time in pre-industrial control run
   calculate normalisation from pre-industrial control run (using method specified by the user)
   normalise data
   return stitched and normalised data
else
   return stitched data
end if
```

These stitched timeseries are a key part of our dataset. They contain many key climate signals, such as interannual (for monthly data) and multi-decadal variability.

However, there can be an extra step. The extra step is de-drifting or applying 'normalization'. In this context, normalization refers to calculating anomalies from some reference values. In some cases, this is trivial. For example, taking anomalies from a given period within the existing output, for example, calculating anomalies relative to the 1850–1900 period.

Nonetheless, there are many cases which require more complex analyses. For example, calculating anomalies relative to a 21-year (or 30-year) running mean of the equivalent period in the pre-industrial control run. Such a calculation requires finding the pre-industrial control data, identifying the equivalent period in the pre-industrial control run, correctly lining it up with the data to be normalized before finally calculating the anomalies. This can be done for single ensemble members (Figure 2) and for multiple members (in which case particular care must be taken to normalize each ensemble member against the correct period from the pre-industrial control run, Figure S1). For small subsets of the data, this can be done manually; however, automated solutions are necessary to perform it over an entire CMIP archive.

Within our dataset, we currently offer four different normalization options (in addition to the outputs which have had no normalization applied). Before describing these options, we stress that all of our processing data are openly available so users who wish to use different normalization options to the ones provided are able to do so. Our four different normalization options are anomalies and de-drifting with 21- and 30-year running means as reference values. The anomalies are calculated as the difference between the model output and the corresponding running mean from the pre-industrial control experiment. In contrast, the de-drifting calculations simply remove any drift in the running mean of the pre-industrial control experiment, without calculating differences. The anomaly calculations are useful for variables such as *tas* (surface air temperature), where changes in the variable from the pre-industrial state are of most interest. The de-drifting calculations are used for variables such as *cLand* (total carbon in all terrestrial pools), where the absolute values are of importance, but it is also important to remove model drift before performing further analysis.

For all normalization options, we use an equation of the form:

$$v_{\text{norm}}(r,t) = v_{\text{raw}}(r,t) - v_{\text{pi}}(r,t) \tag{2}$$

where $v_{\text{norm}}(r,t)$ is the normalized values for region r at time t, $v_{\text{raw}}(r,t)$ is the raw values and is $v_{\text{pi}}(r,t)$ the running-mean reference values from the pre-industrial control run (either absolute values or drift values depending on the normalization method).

2.2.3 | Retracted data

CMIP data are occasionally found to be erroneous and hence retracted (Balaji et al., 2018). To handle this, as part of netCDF-SCM, we provide a simple tool which checks if a data file is based on any retracted data (see https://netcdf-scm.readthedocs.io/en/latest/usage/using-cmip-data.html, last accessed 25 June 2020). In addition, the tool will also examine the data's licence and, to the extent possible, warn the user about any non-standard licence terms.

These tools take advantage of CMIP6's 'dataset-centric rather than system centric' approach (Balaji et al., 2018). The dataset-centric approach allows data users to check the validity of their data at point of use, rather than relying on the data provider to have done this for them. The dataset-centric approach also ensures that 'dark repositories' (Balaji et al., 2018), such as our derived dataset, maintain the connection between data user and the original source of the data. In our derived dataset, we maintain this connection by providing the persistent identifiers of all datasets within our metadata (specifically the tracking_id attributes).

3 | DATASET ACCESS

The dataset described in this paper is openly available at https://doi.org/10.5281/zenodo.3951890, and all our data processing code is openly available at https://gitlab.com/netcdf-scm/calibration-data. Any use of the data must follow CMIP's terms of use (see discussion in Section 2.1).

At present, our dataset contains timeseries for over 100 models and 40 experiments of interest from the CMIP5 and CMIP6 archives. In total, we have over 40,000 timeseries. To date, we have processed 83 variables, full descriptions of which are available in the 'Model output specifications' section of https://pcmdi.llnl.gov/CMIP6/Guide/dataUsers.html (last accessed 8th October 2020). If users would like extra variables, we are happy to discuss adding more into our dataset. Our current variable list is: energy flux and temperature variables – *hfds*, *rlut*, *rsdt*, *rsut*, *tas*, *tasmin*, *tasmax*, *tos*, *ts*; precipitation – *pr*; carbon cycle related variables – *cLand*, *cLitter*, *cLitterGrass*, *cLitterShrub*, *cLitterSubSurf*, *cLitterSurf*, *cLitterTree*, *cMisc*, *cOther*, *cProduct*, *cSoil*, *cSoilFast*, *cSoilMedium*, *cSoilSlow*, *cStem*, *cVeg*, *cVegGrass*, *cVegShrub*, *cVegTree*, *cWood*, *co2mass*, *co2s*, *fAnthDisturb*, *fBNF*, *fDeforestToAtmos*, *fDeforestToProduct*, *fFire*, *fFireAll*, *fFireNat*, *fGrazing*, *fHarvest*, *fHarvestToAtmos*, *fHarvestToProduct*, *fLitterSoil*, *fLuc*, *fNAnthDisturb*, *fNLitterSoil*, *fNProduct*, *fNVegLitter*, *fNdep*, *fNfert*, *fNgas*, *fNgasFire*, *fNgasNonFire*, *fNloss*, *fNnetmin*, *fNup*, *fVegLitter*, *fco2antt*, *fco2fos*, *fco2nat*, *fgco2*, *gpp*, *nbp*, *nep*, *netAtmosLandCO2Flux*, *npp*, *nppGrass*, *nppOther*, *nppShrub*, *nppTree*, *ra*, *rh*, *rhGrass*, *rhLitter*, *rhShrub*, *rhSoil*, *rhTree*; nitrogen cycle related variables – *nLand*, *nLeaf*, *nLitter*, *nMineral*, *nProduct*, *nRoot*, *nSoil*, *nStem*. We include output for 11 large-scale regions (World, Northern Hemisphere, Southern Hemisphere, ocean, land, Northern Hemisphere ocean, Northern Hemisphere land, Southern Hemisphere ocean, Southern Hemisphere land, North Atlantic Ocean and the El Niño 3.4 region, defined

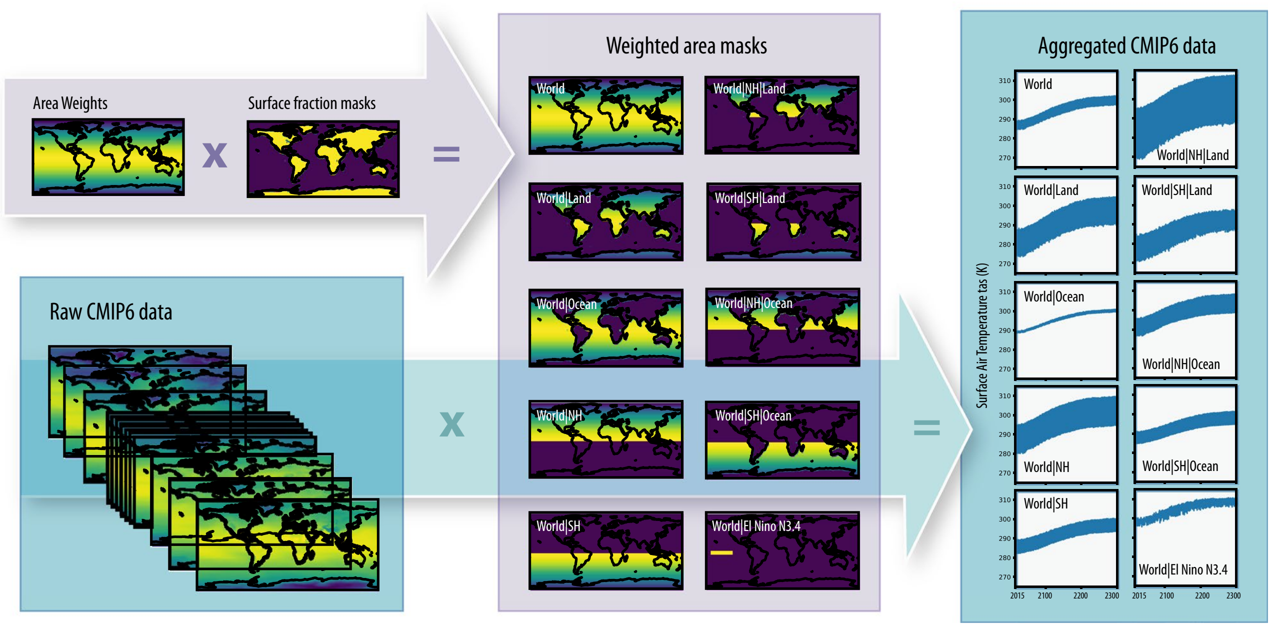

FIGURE 1 Data processing workflow. Firstly, raw data are combined with cell area and surface fraction information to derive area weighted masks for each region. The region-specific masks are then combined with the raw CMIP6 data to derive weighted-mean timeseries for each region of interest (here NH stands for 'Northern Hemisphere' and SH stands for 'Southern Hemisphere'). The resulting timeseries require a fraction of the original data's volume hence are much easier to handle for non-experts

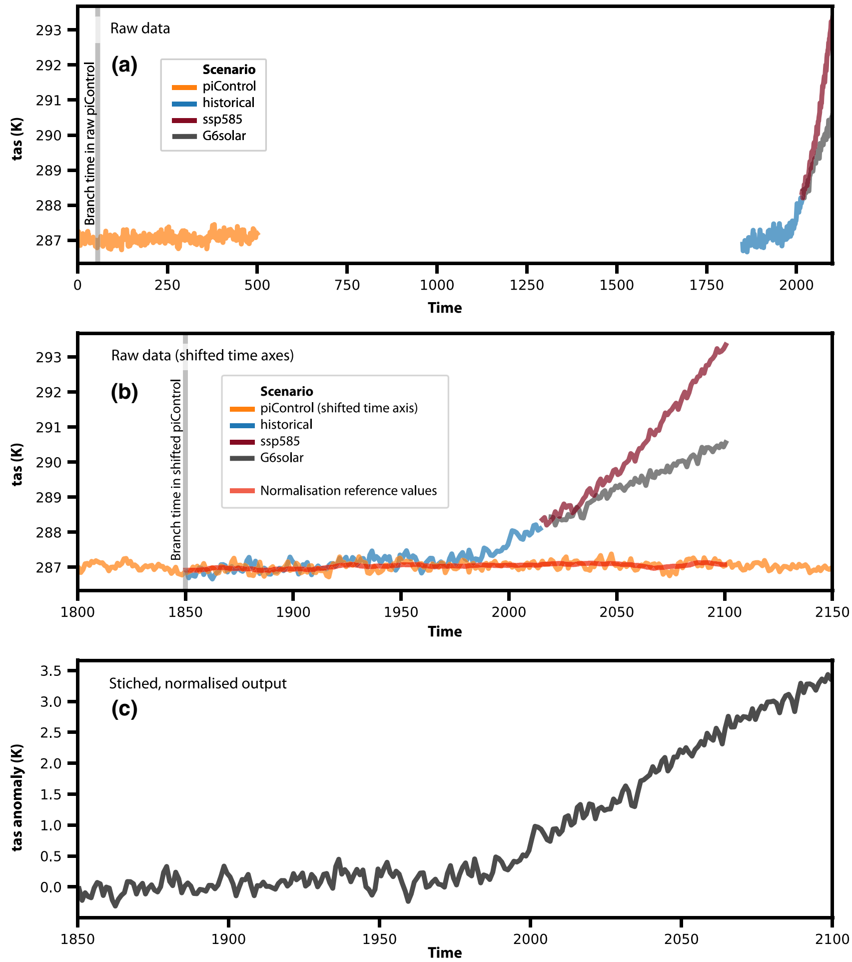

FIGURE 2 Joining of timeseries ('stitching') and calculation of anomalies from the pre-industrial control runs ('normalization'). Following CMIP6 terminology, we show here a 'family' of experiments, with G6solar being the child, ssp585 being the parent, historical being the grandparent and piControl being the great-grandparent. (a) raw data on its native time axes; (b) raw data alongside the pre-industrial control run, with the pre-industrial control run's time axis shifted so the branch point (i.e. the point in time at which an experiment branches from its parent, in this case the point in time at which the historical experiment branches from the piControl experiment) occurs at the same time in the pre-industrial control run and the historical experiment; (c) final stitched and normalized output. In this case, the stitched and normalized output comprises the historical experiment from 1850–2014, the ssp585 experiment from 2015–2019 and the G6solar experiment from 2020–2100 and has been normalized against a 21-year running mean of the pre-industrial control experiment (red line in panel b)

as the region within 5 N–5°S and 170 W–120 W) and, by using the regionmask package (Hauser et al., 2020), all of the IPCC climate reference regions defined by Iturbide et al. (2020).

The timeseries are continuous, monthly timeseries for specific variables, experiments and regions of interest for a selection of the CMIP5 and CMIP6 archives. These timeseries are the combination of the experiment of interest, any (potentially multiple) experiments from which it 'branched' and any normalization, which is applied (Section 2.2 and Figure 2).

Our dataset is a different product compared to the data available in the IPCC AR6 Atlas (https://github.com/SantanderMetGroup/ATLAS, last accessed 9th October 2020). At present, the only similarity is that both our dataset and the Atlas provide surface air temperature (*tas*) at various regional aggregations for tier 1 experiments from CMIP5 and CMIP6. However, while the Atlas uses a binary land/ocean mask (i.e. each value is a one or a zero) and cosine of latitude as a proxy for area weights, we use the model reported cell areas (where available) and a continuous land fraction (including subtleties for land-only and ocean-only data, see Section 2.2.1) to calculate weighted, aggregate metrics. Secondly, we provided stitched outputs, joining each experiment with its parent, grandparent etc. experiments. Thirdly, the Atlas provides precipitation (*pr*) timeseries, whereas we do not provide precipitation. Instead, we provide data for 82 other variables as described previously. Finally, the Atlas provides one ensemble member per climate model, while we provide as many ensemble members as are available.

We provide our data in a comma separated value (csv) format. This format is composed of three key parts and uses the extension. MAG because it is directly compatible with the MAGICC7 reduced complexity climate model (Meinshausen et al., 2019). The first part is the header, which contains the date the file was written, the contact for the file, the version of netCDF-SCM used to crunch the data and the version of Pymagicc (Gieseke et al., 2018) used to write the file. The second is the metadata. This contains all metadata from each of the raw datafiles, plus extra information and metadata about the method used to derive the final timeseries included in the file. It also contains a FORTRAN90 name list with basic information about the data in the file. A particularly useful bit of information is the THISFILE_FIRSTDATAROW line, which allows automated readers to skip to the line of interest if they are only interested in the data. The third and final section is the data. The data block is composed of a four-line header with variable, units and region information for each timeseries as well as a MAGICC7-specific row, TODO, which can generally be ignored. After the header comes the data itself. The data block has column-oriented data, with the first column being the time axis (in years) and each subsequent column being a different timeseries (sometimes referred to as 'wide' data although this term is imprecise (Wickham, 2014).

The data archive grows as we add new CMIP6 results. An up-to-date full collection (alongside instructions for automated downloads) can be found at https://cmip6.science.unimelb.edu.au. Examples of how to use the data can be found in https://gitlab.com/netcdf-scm/calibration-data/-/tree/master/notebooks (last accessed 25 June 2020), and we encourage any users of the data to add further examples, especially in computing languages other than Python.

4 | POTENTIAL DATASET USE AND REUSE

The key users of this dataset are reduced complexity climate modellers. These regional-aggregate timeseries are a key part of model calibration (see, e.g., Meinshausen et al. (2011)) and comprehensive datasets allow reduced complexity models to be validated over a wide range of experiments and output variables.

Having said this, we believe that the dataset can be useful well-beyond the reduced complexity climate model community. As discussed in Section 1, processing CMIP data is an intimidating task for expert users and not possible for those without specialist training. We hope that our aggregate dataset removes this need for specialist training, thanks to its significantly reduced data volume and text-based format. As a result, the dataset presented here may be useful to climate change researchers outside the climate modelling community, policymakers, businesses and even journalists.

The dataset presented here comes with three important caveats. The first is that we make no guarantees about how up-to-date our data is. As discussed previously, the onus is on users of the data to check for retractions before using the data (see Section 2.2.3 for discussion of our automated tool for checking such retractions). The second is that the area-weighting used (Equation (1)) is only one of many possible area-weighting choices. For example, other users may wish to partition data into area/land boxes based on whether the fraction of each gridbox is above some threshold or not. At present, we do not provide data for area-weighting choices beyond the one described in this paper. For users who need to do such analysis, we are able to provide guidance on how this could be done with netCDF-SCM via netCDF-SCM's issue tracker (https://gitlab.com/netcdf-scm/netcdf-scm/-/issues). Thirdly, we provide only a limited number of ways of calculating anomalies. Again, for users who wish to calculate anomalies in a different way to what we have provided, netCDF-SCM's issue tracker can be used for discussions and guidance.

On the software side, the netCDF-SCM tool is in its relative infancy and is currently only developed by a limited community. As a result, many improvements could be made. We hope that netCDF-SCM's open source nature, with its extensive tests, invites contributions from throughout the climate community and beyond. Such contributions will improve netCDF-SCM's functionality and reduces the need for duplicate effort.

As a first suggestion, we note that much of netCDF-SCM's functionality is a duplication of functionality within the ESMValTool, 'A community diagnostic and performance metrics tool for routine evaluation of Earth system models in CMIP' (Eyring et al., 2016b). The duplication results from the parallel development of these two projects, which were both too immature to be combined when they were begun. Adding netCDF-SCM's functionality into the ESMValTool, which is a much bigger and better supported project, would reduce this duplication and likely provide benefits for both groups.

Outside of integration with the ESMValTool, improvements could be made to netCDF-SCM's memory usage, dask usage and parallelization. These may lead to significant processing performance as such optimizations, particularly the use of dask's task planning capabilities, have only been performed to a limited degree to date.

5 | CONCLUSIONS

We have presented a dataset of monthly, global, hemispheric and land/ocean means based on the CMIP5 and CMIP6 archives. The dataset is aimed at reduced complexity climate modellers, but may also be useful for many other researchers. Our dataset joins the different levels of experiments, reducing the need for users to manage and join multiple separate datasets before they can be used. This dataset is orders of magnitude smaller than the raw datasets themselves hence can be managed much more easily by non-expert users. In addition, we provide the dataset in a text-based format, which removes the need for users to be familiar with the netCDF format before they can use the data. We hope this facilitates use by groups outside the science community, for example policymakers, actuaries and journalists.

We add new CMIP6 results to our dataset regularly and simultaneously remove any data derived from retracted datasets. We also provide simple tools to check whether a user's data have been retracted since they downloaded the data and to highlight any non-standard licence terms so that users can make sure they have the most up-to-date information possible.

We hope this can be a great community resource, which builds on the community efforts of the netCDF format (Unidata, 2020), Iris (Met Office, 2019) and generations of CMIP (Taylor et al., 2012; Eyring et al., 2016a).

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CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

OPEN PRACTICES

This article has earned an Open Data badge for making publicly available the digitally-shareable data necessary to reproduce the reported results. The data is available at https://doi.org/10.5281/zenodo.4536523 Learn more about the Open Practices badges from the Center for OpenScience: https://osf.io/tvyxz/wiki.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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